

Pulse Arrival Time estimation based on Electrocardiography and Bioimpedance measurements in non-standard points

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Abstract--Arterial stiffness and blood pressure can be diagnosed by estimating the pulse arrival time (PAT). To do so, electrocardiography (ECG) and impedance plethysmography (IPG) methods are employed. In this paper we propose a non-invasive, low-cost approach that uses non-standard points to measure the electrocardiogram and the bioimpedance. To determine if the ECG and BIM-IPG can be properly measured in the upper extremities open new doors to the design of comfortable portable devices that could constantly be monitoring the user outside hospital environment. This could be especially interesting for patients that suffer of chronic circulatory diseases. Performed tests in the laboratory show the validity of the proposed method.

I. INTRODUCTION

THE current and more common methodologies to keep track of the pressure and arterial stiffness of the patient are respectively, blood pressure cuffs and Doppler echocardiography. Blood pressure cuffs are obviously uncomfortable for the user, thus prolonged measurements are difficult to perform. Doppler echocardiography is expensive and only available in hospitals. It follows that it is also uncomfortable for the patient and continuous monitoring is not possible.

It has been proven from the measurement of both the heart electrical signal and the blood flow mechanical signal, that an estimation of the arterial state and the blood pressure could be obtained [1, 2]. The parameter that allows us to do such an estimation is a temporal parameter known as PAT (Pulse Arrival Time) [3].

The term PAT is defined as the time delay between a characteristic feature of the electrocardiogram (ECG), typically the R wave, and a point of an arterial pulse waveform (Fig. 1) [4].

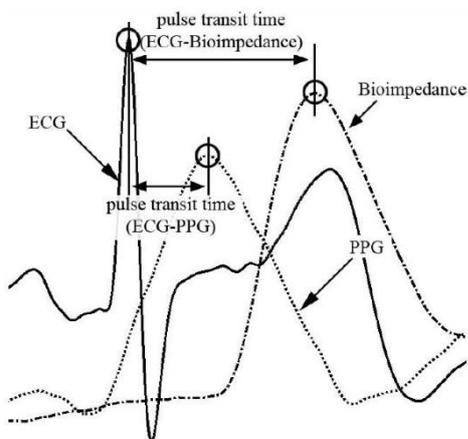


Fig. 1: Important points in PAT measurement.

Photoplethysmography (PPG) is commonly used to pick the pulse waveform in order to measure the PAT. But the design of PPG sensors is uncomfortable for the subject and

a lot of noise gets introduced due to environmental light. In this work, measuring the bioimpedance (BIM) is proposed as an alternative method since inexpensive easily-placeable electrodes are needed and less interferences affect the signal.

The BIM signal shows the change of the circulatory vessels impedance when the pressure pulse propagates along them. A mathematical model in [5,6] relates the blood vessels, approximated to cylindrical, and the variation of the volume of them:

$$\Delta V = -\frac{\rho L^2}{Z_0^2}(\Delta Z_\rho + \Delta Z_v)$$

where ΔV is the voltage variation aforesaid, ρ is the resistivity of the tissue, Z_0 is the basal impedance of the present tissues, ΔZ_ρ and ΔZ_v are the impedance variations due to resistivity and vessels volume changes, respectively; and L is the distance between detection electrodes.

Assuming the approximation $\Delta Z_\rho \ll \Delta Z_v$, (although the blood resistivity changes are important in the morphology of the signal, they are so small that can be neglected [5]), it should be possible to obtain the heart rate from impedance measurements between two points of a surface of a volume that encloses major blood vessels. BIM signal can be obtained via BIA (Bioimpedance Analysis), injecting a little AC current and measuring the drop of voltage between these two points.

Obtaining the PAT is by itself a challenging and important step, since the presence of motion artifacts complicates the measurement procedure [7]. However, the innovation we propose in this paper is to record the BIM and ECG signals in an upper extremity. Since the ECG is usually recorded in the standard derivations, the question of whether it is possible to measure the ECG in an extremity was still unanswered before our studies. This would improve the comfort of the patient and therefore, ease a continuous PAT tracking.

II. INSTRUMENTATION

The hardware used can be divided into the hardware for detecting ECG (Fig. 2) and the hardware for detecting BIM (Fig. 3). It has been designed so as to improve as much as possible the SNR (signal-to-noise ratio) and the CMRR (common-mode rejection ratio).

Two main interferences may affect our measurements: noise and common-mode interference. In order to quantify how much these interferences disturb the desired signal, two parameters are usually defined: the SNR and the CMRR. In our cases, high CMRR is needed both in the ECG and in the BIM. In the ECG, the 50 Hz interference introduced by the AC electrical facilities has to be rejected. In the BIM, we have to ensure that no interference might appear in the 10 kHz carrier wave.

The ECG hardware functioning in Fig. 2 can be described using five blocks. (1) Electrodes attached to voltage followers. (2) High-pass differential filter at a cutoff frequency of 0.5 Hz. The filter removes the offset and its symmetry forces a high CMRR (ideally infinite). (3) Instrumentation amplifier (INA118) of Texas Instruments. Only by manually changing one resistance, the system gain can be modified. (4) AC coupling network at 0.5Hz so as to reject the common-mode tensions induced by the INA118. (5) Sallen Key low-pass filter with a 200 gain factor and a cutoff frequency of 100 Hz so as to improve the SNR. (6) Connection to a National Instruments data acquiring device (NI-USB 6259).

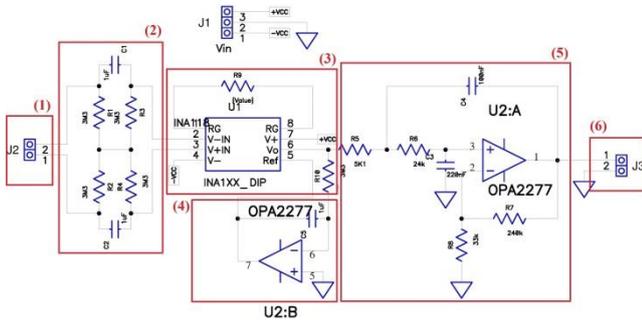


Fig. 2: ECG acquisition system.

The operation of the BIM-IPG measuring circuit can be explained in eight blocks (Fig. 3). (1) High-pass differential filter at a 100Hz cutoff frequency. The symmetry of the filter improves the CMRR. (2) Instrumentation amplifier INA122. (3) AC coupling network at 100Hz to reject the common-mode interferences. (4) Comparator that generates a rectangular signal. (5) Multiplier to demodulate the signal. Multiplies the measured signal with the rectangular signal. (6) Low-pass filter at 10Hz to keep the demodulated continuous component. (7) High-pass filter at 0.5Hz to remove offset and respiratory signal (8) Amplifier and low-pass filter at 10Hz so as to increase the SNR.

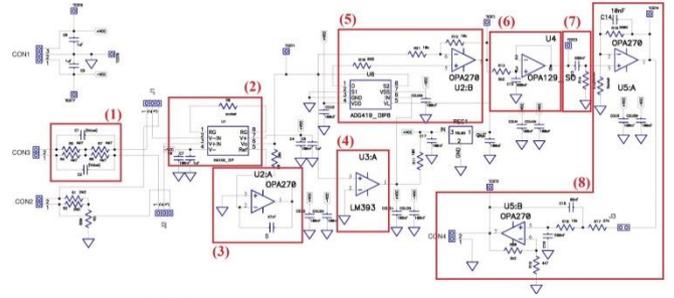


Fig. 3: BIM-IPG acquisition system.

III. MATERIALS AND METHODOLOGY

For the ECG measurement, two dry electrodes have been connected to the ECG system. In order to determine the ECG's detection limit, measures have been performed between: hand-hand, chest-wrist, armpit-hand and elbow-wrist. As it can be seen in Fig. 6, the armpit-hand points are the only positions in the arms where the ECG can be detected (the arrangement is described in Fig. 4). Consequently, from now on we will only measure the ECG and BIM on the positions specified by Fig. 4.

For the BIM measurement, four wet Ag/AgCl electrodes connected to the BIM system were employed. To record the best possible BIM signal, we should try to keep a large enough distance between the positive and negative electrodes. However, to improve PAT detection, we are interested on placing all the electrodes as far away as possible from the heart. The position for the BIM electrodes that best fulfills these demands is elbow-wrist. Using four electrodes instead of two minimizes the error caused by the effect of the electrode-skin impedance [6]. The two outer electrodes inject the test current while the two inner ones measure the voltage. The test AC current was 1 mA with a frequency of 10 kHz.

A Nickel Cadmium Battery of 6V is used for supplying the whole system in order to ensure the safety of the subject and their isolation from the electrical network. Regarding the data acquisition, the NI-USB-6259 device is used. It is 16 bits, controlled from a laptop by a LabView program, and it is able to work at 1Mbit/s. But in this test a 1kbit/s rate was used in each channel.

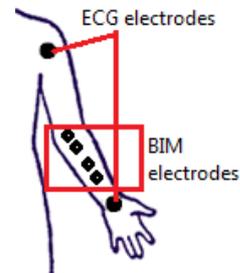


Fig. 4: Electrodes positions for measurements.

IV. SIGNAL PROCESSING

The signals have been subjected to two different procedures:

A. Filtering.

Our hardware has been designed to improve the SNR as much as possible. In spite of this, if the SNR is not good enough, we need to digitally filter the signal.

However, care must be taken, since filters affect the phase of the output, introducing time delays. Time delays in our signals directly affect the accuracy of our PAT measurements, as PAT is a time difference between the ECG R peak and the BIM peak.

The only way to avoid these effects is to ensure that the time delay caused by the filters is smaller than our system resolution (1 ms). If not possible, filtering will add an uncertainty to the PAT detection. Therefore, we must find a balance between the SNR and the delays introduced into our signals.

Of course, there exist ways to reduce this uncertainty, but it is difficult to completely remove it. One method could be the following one: compare the original signal with the filtered signal and measure the delay for each pulse. Mention that the frequency of the signal changes with time (more or less depending on our physical activity while measuring), thus, the delays induced by the filters will also slightly change with time. The highest delay would be the uncertainty of our measurement. Then, two steps could be taken. The easiest and the most reasonable one would be to average all the induced delays and subtract them to our uncertainty. This would reduce significantly our uncertainty but not completely delete it. The most difficult and professional one would be to do an instantaneous calibration of the signal at each pulse. This would completely remove the filter induced delay.

However, the uncertainty induced due to filtering is pretty small in general, so average and subtract is a good enough approach if needed.

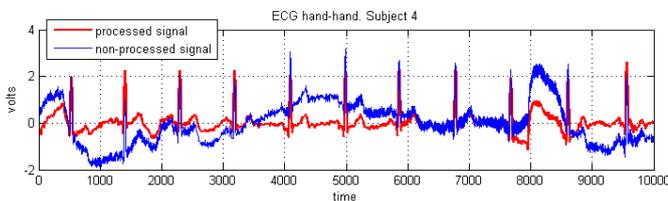


Fig. 5: ECG signal (top) and BIM signal (bottom) both simultaneously detected at the points.

In this paper, filtering is not only used to improve the SNR but also to remove the signal offset. Motion artifacts can strongly vary the offset, resulting in a signal like in Fig. 5 (blue). If a digital high-pass filter at 0.5Hz was not applied, peak detection would be much more difficult.

Last but not least, mention that our filters do not introduce any delay in the samples.

B. Peak detectors.

Several self-developed MATLAB algorithms have been implemented in order to determine the ECG R peak and the BIM peak. From this data, PAT is obtained.

V. RESULTS

Data from four different people has been obtained. The subjects' data is shown in Table 1. In fig. 6, we can appreciate the shape of an ECG and BIM signal.

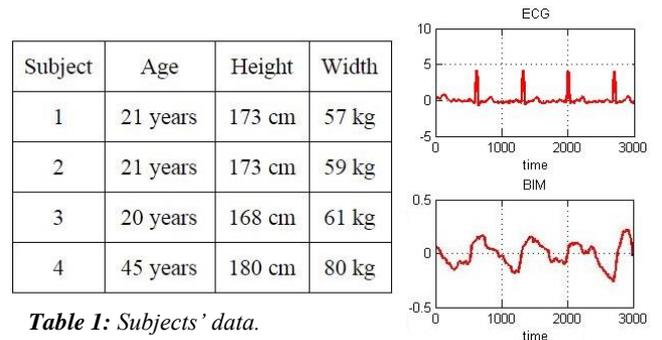
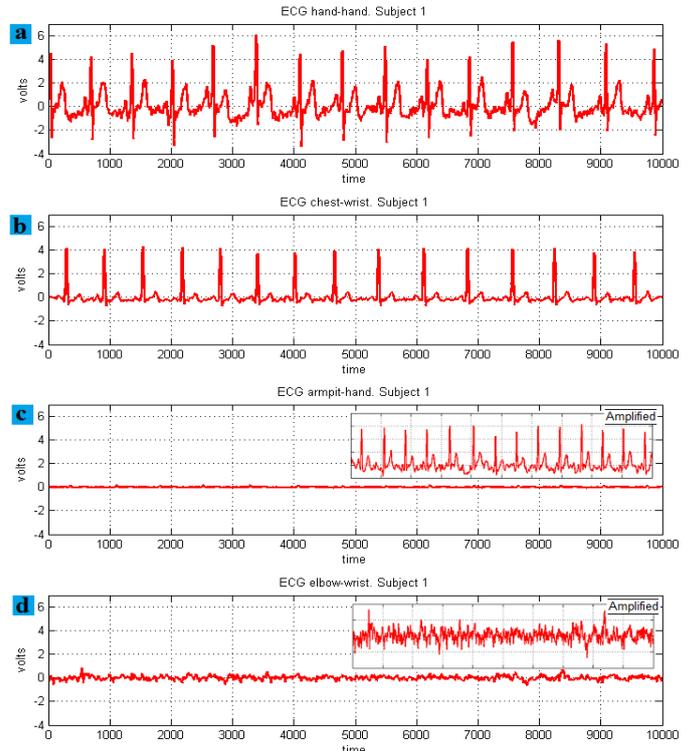


Table 1: Subjects' data.

Fig. 6: (a) ECG hand to hand. (b) BIM in the arm.

To answer if it is possible to measure the ECG in an extremity, it is shown in fig. 7. The larger the distance between the electrodes, the higher the ECG signal



amplitude.

Peaks can be detected until the signal gets too small with respect to the noise amplitude (fig. 7 (d)). However, fig. 7 (c) shows that the ECG signal between the armpit and the hand can be measured. Therefore, we have achieved one of our goals, to prove ECG signal can be measured in an extremity.

Fig. 7: ECG measured for Subject 1 in positions (a) hand-hand, (b) chest-wrist, (c) armpit-hand, (d) elbow-wrist.

Now, we move on to detect the PAT. In Fig. 8 the correct detection of the ECG and BIM peaks can be appreciated. For these signals, the ECG electrodes have been placed between the armpit and the hand and the BIM electrodes between the elbow and the wrist.

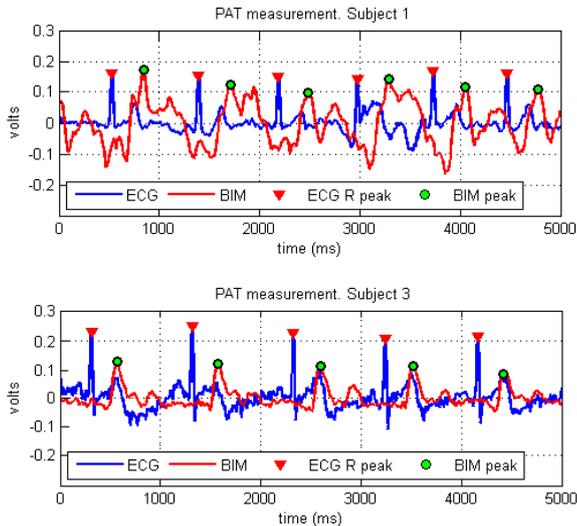


Fig. 8: PAT detection for Subjects 1 and 3.

The PAT results for Subject 1, 3 and 4 are presented in Table 2. The level of confidence is 95%, using a coverage factor of 2.

Subject	PAT $\pm 2\sigma$ (ms)
1	317 \pm 34
3	270 \pm 26
4	283 \pm 38

Table 2: PAT results for three subjects.

The lowest PAT is obtained for the youngest subject as the reader may expect. However, the highest PAT is not obtained for Subject 4 but for Subject 1. Does this mean that the forty-year old subject (Subject 4) is healthier than a twenty-year old? Not necessarily. In fact, what these results prove are the variability of PAT, hence the variability in blood pressure (BP) [8] in each person, and that calibration must be done for each individual [9].

VI. CONCLUSIONS

In this paper, a non-invasive and low cost PAT detection approach using the ECG and BIM measured in non-standard points has been presented. This achievement opens the door to the development of a comfortable portable device that could be continuously monitoring the PAT's user.

The PAT is a useful parameter to infer blood pressure and arterial stiffness. However, it is difficult to obtain since it is highly variable (as it is correlated with the variability of the

heart rate) as well as it changes from subject to subject in a fashion not related to the state of the patients circulatory system (see Table 2). Currently, individual calibration must be performed. Nevertheless, it is a future major challenge to develop a uniform and accurate calibration procedure for all the population. This will open the door to a 24/7 low-cost monitoring device. As the system requires only inexpensive components and a laptop, this potential PAT measurement device could be available even for third-world countries.

New models are being developed in order to deduce the blood pressure and the arterial stiffness from the PAT. This work could help to future developments in the models because with a portable device, constant monitoring could be achieved, and therefore a study of the signal evolution over time could be performed. Despite we have achieved our initial goals, our results are conditioned by the limitations of the devices. We foresee that with better instrumentation, the ECG can be obtained from even closer points in the extremities.

VII. REFERENCES

- [1] R. Couceiro, P. Carvalho, R. P. Paiva, J. Muehlsteff, J. Henriques, V. Schulze, A. Ritz, M. Kelm, C. Meyer, "Characterization of Surrogate Parameters for Blood Pressure Regulation in Neurally-Mediated Syncope", Conf Proc IEEE Eng Med Biol Soc. 2013;2013:5381-5. doi: 10.1109/EMBC.2013.6610765.
- [2] Muehlsteff J, Ritz A, Drexel T, Eickholt C, Carvalho P, Couceiro R, Kelm M, Meyer C., "Pulse Arrival Time as surrogate for systolic blood pressure changes during impending neurally mediated syncope.", Conf Proc IEEE Eng Med Biol Soc. 2012; 2012:4283-6. doi: 10.1109/EMBC.2012.6346913.
- [3] Espina, J.; Falck, T.; Muehlsteff, J.; Yilin Jin; Adan, M.A.; Aubert, X., "Wearable body sensor network towards continuous cuff-less blood pressure monitoring," *Medical Devices and Biosensors, 2008. ISSS-MDBS 2008. 5th International Summer School and Symposium on*, vol., no., pp.28-32. doi: 10.1109/ISSMDBS.2008.4575008
- [4] Suyoung Bang; Changik Lee; Jinwoo Park; Min-Chang Cho; Young-Gyu Yoon; SeongHwan Cho, "A pulse transit time measurement method based on electrocardiography and bioimpedance," *Biomedical Circuits and Systems Conf, 2009. BioCAS 2009. IEEE*, vol., no., pp.153,156, 26-28 Nov. 2009 doi: 10.1109/BIOCAS.2009.5372060.
- [5] J. Gomez-Clapers, R. Casanella and R. Pallas-Areny, "Pulse Arrival Time Estimation from the Impedance Plethysmogram Obtained with a Handheld Device", *IEEE Conf Proc IEEE Eng Med Biol Soc. 2011; 2011:516-19.* doi: 10.1109/IEMBS.2011.6090093.

- [6] Tushar Kanti Bera, "*Bioelectrical Impedance Methods for Noninvasive Health Monitoring: A Review*," Journal of Medical Engineering, vol. 2014, Article ID 381251, 28 pages, 2014. doi:10.1155/2014/381251.
- [7] Muehlsteff, J.; Aubert, X.A.; Morren, G., "*Continuous cuff-less blood pressure monitoring based on the pulse arrival time approach: The impact of posture*", Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE, vol., no., pp.1691-1694. doi: 10.1109/IEMBS.2008.4649501
- [8] Pinheiro, E.; Postolache, O.; Girao, P., "*Pulse arrival time and ballistocardiogram application to blood pressure variability estimation*," Medical Measurements and Applications, 2009. MeMeA 2009. IEEE International Workshop on, vol., no., pp.132-136. doi: 10.1109/MEMEA.2009.5167970
- [9] Yinbo Liu; Poon, C.C.Y.; Yuan-Ting Zhang, "*A hydrostatic calibration method for the design of wearable PAT-based blood pressure monitoring devices*," Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE, vol., no., pp.1308-1310. doi: 10.1109/IEMBS.2008.4649404